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Water use efficiency of TOMATOES in greenhouses and hydroponics

Massive amounts of water are required for the production of our food, varying from several cubic metres per kilogram of beef to as low as 4 litres per kilogram for tomatoes grown in high-tech glasshouses. This article by ELLY NEDERHOFF and CECILIA STANGHELLINI presents data on Product Water Use (PWU) of some foods and discusses how the water requirement for fresh tomatoes can be brought down from 300 to 4 litres/kg.

Water needs

Water is at the base of our food pyramid: all our vegetables, fruit, wheat, meat, etc., are produced with water. It is estimated that the world's water use for crop production is 5,400 km^3 per year and increasing rapidly. More water is needed as the world population grows and as more people want to eat more diverse and special foods. Good quality fresh water is precious; imminent water shortage is one of the largest threats to life on earth. Hence it is of utmost importance to use water efficiently. Water can be scarce due to long-term drought, ground water depletion, excessive water use upstream, or can be of poor quality due to salinisation or pollution. Even where water is in abundance there is a need to use water wisely. Also, it is important to minimise the discharge of fertilisers and agrichemicals into water sources and natural habitats. This article discusses the efficiency of water use for primary production.

Product Water Use (PWU)

Studies on water by UN, OECD, FAO etc., use some interesting concepts, for instance, *Water Footprint, Virtual Water, Product Water Use* and *Water Use Efficiency.*

Product Water Use (PWU) is the volume of water necessary during the entire production period to produce one kilogram of fresh product, and is expressed in litres/kg.

Water Use Efficiency (WUE) is similar but the other way round: it is the production in kilograms, divided by the litres of water used for growing, and is expressed in kg/litre.

Water is used efficiently when PWU is low and WUE is high. In the past the term WUE was often used, while now PWU seems to be the preferred term. PWU and WUE of a food product are calculated from recorded yield and water consumption data over the whole cropping season. Production is straightforward, but water supply can be harder to measure. PWU and WUE are both calculated from water consumption and production. It will be shown in this article that variation in water consumption or in production or both can cause large differences in water efficiency.

PWU of some foods

The Water Footprint Network (Hoekstra and Chapagain, 2008) has collected and published an extensive data set for hundreds of products for 65 countries. See *Table 1* with average Product Water Use figures in litres/kg (this is kilogram 'fresh' product). Tea, coffee, meat, rice, wheat and dry beans are big water users. Beef is amongst the largest water consumers: nearly 16,000 litres (16 m^3) of water is needed to produce 1 kg of beef. Other animal-based products too require a lot of water. Most fruit and vegetables are relatively modest in water use, while fodder has the lowest PWU. It must be noted that there are enormous variations between countries.

The huge differences and variations are explained by several main factors. Crops in hot climates transpire a lot more water than crops in moderate climates (not shown in *Table 1* except for tomatoes in the last lines).

Production of meat includes drinking water for the animals plus water to grow the grass or fodder eaten by the animals. Where animals are produced indoors it also involves servicing water.

Figure 1. Product Water Use (PWU) in litres of water for 1kg of fresh tomatoes grown in a drip-irrigated field or in greenhouses. Source: Stanghellini.

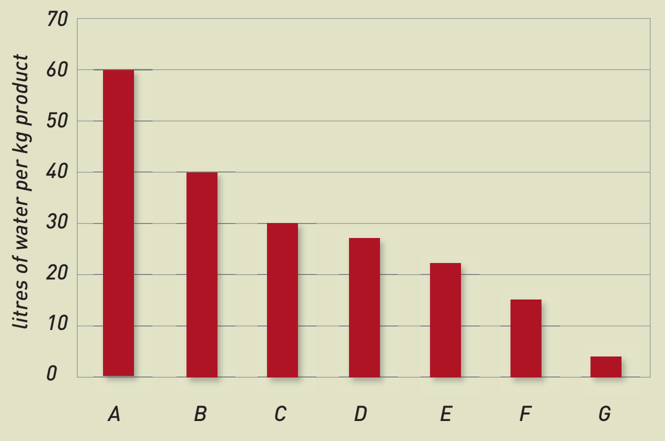

Table 1. *Product Water Use in litres per kilogram, world averages based on 65 nations over period 1997-2001. For details see the source: A.Y.Hoekstra (2009), www.waterfootprint.org*

Product	PWU (litre/kg)
Tea	24,960
Cashew Nuts	19,271
Coffee, Green	17,373
Beef, boneless, fresh	15,497
Ham, preserved	6,443
Cheese	4,914
Olives	4,393
Beans, Dry	4,253
Eggs in shell	3,340
Rice, Paddy	2,291
Soybeans	1,789
Asparagus	1,473
Apricots	1,391
Wheat	1,334
Milk 1% fat	990
Bananas	859
Apples	697
Grapes	655
Oranges	457
Kiwi Fruit	430
Beans, Green	359
Strawberries	276
Pumpkins, Squash	234
Onion, Green	214
Cabbages	211
Tomatoes	**184***
Watermelons	160
Cauliflower	159
Spinach	144
Maize, Forage + Silage	143
Lettuce	133
Carrots	131
Veges + Roots, Fodder	78
* Tomatoes (tropics)	200-900
* Tomatoes (cool)	8-150


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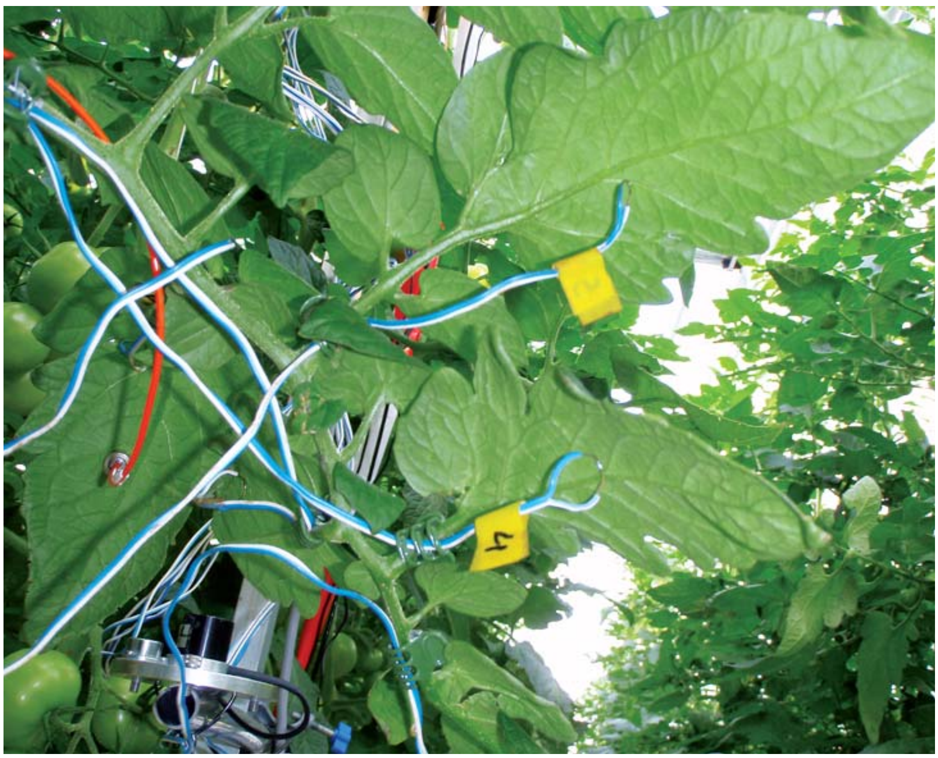


A
B

Water content of a product is a major factor, too: it takes more water to produce a dry product (e.g. rice) than a watery product (e.g. cucumber), although that may seem contradictory at first sight.

Harvest Index is another factor, namely, whether the whole plant is consumed (fodder and lettuce) or only a small part (tree nuts).

We won't go into any detail, other than to say that Table 1 demonstrates that production of vegetables roughly uses in the order of 1% of the water that beef production requires. We will see later that tomatoes can be produced with considerable less water again.

PWU of tomatoes

Table 1 (last lines) shows Product Water Use for a range of crops including tomatoes. This is per kilogram of fresh tomatoes. 'Fresh' is important, as tomatoes consist of 95% water: if the data were expressed as water use per kilogram 'dry' product, the figures would be about 20 times higher.

Table 2 presents PWU data collected by our own group for tomatoes in various countries and growing systems. Between 4 and 300 litres of water is required for every 1 kg of fresh tomatoes. The challenge is how to get down from 300 to 4 litres/kg.

Table 3 presents Product Water Use data from the University of Cordoba in Spain, also as litres of water required for every 1 kg of fresh tomatoes. This study shows that good management reduced PWU about three-fold, and that growing in a greenhouse reduced PWU about five-fold compared to growing in the field. In this study, a well-managed greenhouse cultivating tomatoes uses 13 times less water than for poorly managed field production. This study did not include the high-tech growing systems included in *Table 2*.

Water uptake, transpiration and drain

Of the water supplied to a crop, only a small part is used for actual weight gain, while most of it simply passes through plants and is lost by transpiration. Water used for plant production can be separated into the following:

1. fixation in plants (weight gain, growth) *
2. transpiration by leaves *
3. drain from the root-zone
4. other.

* Together, these two form the water uptake.

Item 1 (fixation in plants) means incorporation of water in the plant to build fresh plant tissue such as fruit, leaves, stems and roots. This part is only small, often in the order of 10% of water uptake. Water fixation creates fresh weight gain, so we don't want to minimise this fraction.

Item 2 (transpiration by leaves) is by far the largest fraction: often it is 90% of water uptake, depending on the conditions.

Table 2. *Product Water Use (PWU) in litres of water for 1kg fresh tomatoes grown in various climates and growing systems. Source: Van Kooten et.al., 2008*

Tomatoes - production method	Country	litres/kg
Open field, general	Various*	100-300
Open field with drip irrigation	Israel	60
Unheated plastic greenhouse ('parral')	Spain	40
Unheated glasshouses	Israel	30
Unheated plastic 'parral', regulated ventilation	Spain	27
Advanced controlled glasshouses with CO2	Netherlands	22
As above with closed hydroponic system	Netherlands	15
As above but closed greenhouse	Netherlands	4
Greenhouse with evaporative cooling	Mexico	Est. 100 **
* Countries: Israel, Spain, Turkey.		
** water for evaporative cooling (estimate only).		

Table 3. *Product Water Use (PWU) in litres of water for 1kg fresh tomatoes grown in the field or in a greenhouse. Original data were for tomato dry weights, but converted here to fresh weight. Source: University of Cordoba, Spain.*

Management	Field	Greenhouse	Average
poor	693	122	407.5
excellent	210	53	131.5
average	451.5	87.5	270

Item 3 (drain from the root-zone) is meant here as any loss of water or nutrient solution from the root zone. It is the water supplied to the soil or growing system that is not taken up by the plants. Drain varies a lot, especially when comparing soil and hydroponics.

Item 4 (other) can include all other forms of using water for crop production. *Items 1* and *Item 2*, together, form the water uptake, while *Item 3* and *Item 4* are not taken up by the plants.

In our data, we have focused on water supply to the plants *(Items 1, 2* and *3)*. We only included 'other' water use in the case where a considerable amount of water is used for evaporative cooling (as indicated).


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From field to hydroponic greenhouse

Here we list the big steps to improve water use efficiency, and in the next paragraphs we describe these steps in more detail.

In field-grown crops the drain can be massive due to leaching to the underground, especially in sandy soils, or due to immediate evaporation after irrigation. The first improvement can be made by improving the soil by adding organic material with better water-holding capacity, or by mulching. A large improvement is made by using drip irrigation, with drippers placed near every plant. Even better is drip irrigation combined with mulching.

A big step up is growing in a greenhouse instead of in the field. This gives a large improvement in water efficiency due to controlled irrigation, increased production and reduced transpiration. Further improvement comes from using a high-tech 'closed' greenhouse with advanced cooling *(see further)*.

The ultimate Water Use Efficiency is achieved by growing vegetables in a closed hydroponic system in a closed greenhouse with advanced cooling. In a recent experiment by the Wageningen University, Product Water Use was as low as 4 litres of water for 1 kg of fresh tomatoes. Turned around, this means 1 m^3 of water produces 250 kg of fresh product.

Greenhouse

Using a greenhouse instead of growing in the field has a large effect on water efficiency. *Table 2* shows two field cultivations and several greenhouse situations. The improvement by growing in a greenhouse is enormous. *Table 3* shows improvement in PWU of about five times for greenhouse-grown product compared to field-grown.

The improved water efficiency comes primarily through higher production and, secondly, through lower transpiration. The increase in production comes from controlled growing conditions (including CO_2 supply), longer season, better varieties, protection from the elements, etc. Transpiration is by far the largest component of water uptake (say 90%) and therefore a reduction in transpiration has a significant impact on water use. Transpiration is driven by radiation, and influenced by humidity (namely, that higher humidity reduces the transpiration). In a greenhouse the radiation is lower than outside, and humidity is higher than outside. These two factors both reduce the transpiration per m^2, resulting in clearly less transpiration inside a greenhouse than outside. Lower transpiration means lower water use, thus improved WUE.

However, there are other factors to consider, too. One is that the growing season in the field is much shorter than in the greenhouse, and for this reason water use can be less in the field than in a greenhouse. On the other hand, in the field a lot of water leaches out, while in the greenhouse the drain water can be collected.

Example

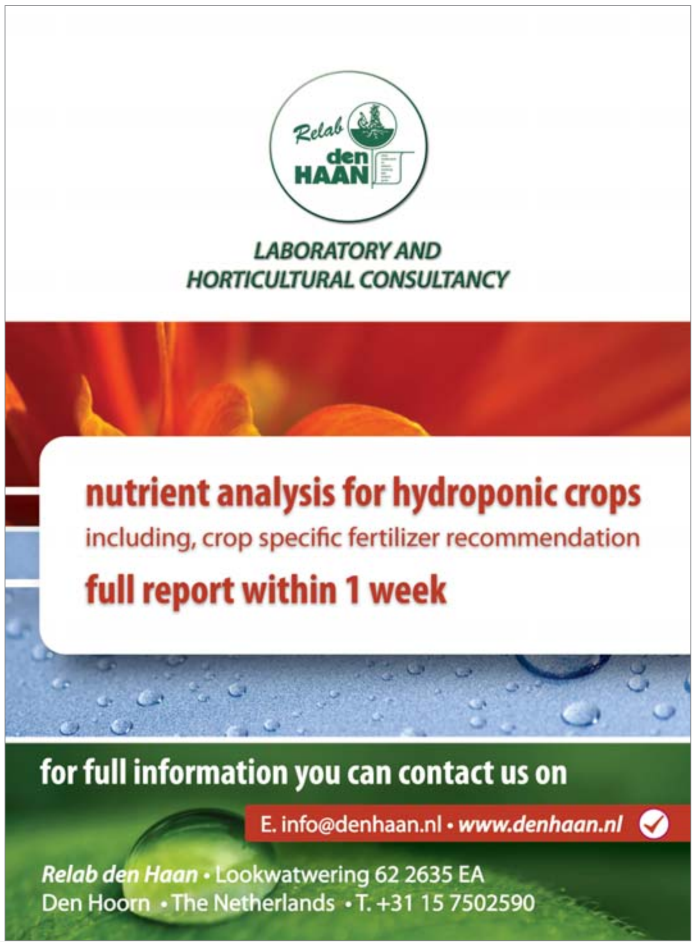
The effect of a greenhouse can best be explained by a numerical example. Production of tomatoes in the field is in the order of 3-8 kg/m^2/year, while in a greenhouse it is 50-80 kg/m^2/year (even 100 kg/m^2/year has been achieved). Thus, the production rate is 10 to 20 times higher in a greenhouse than in the field, and this has a strong effect on PWU.

Water use in the field varies a lot too: it can be, for instance, 300 litres/m^2 over the growing season (part of the year), while water use in Dutch greenhouses is in the order of 1,000 litres/m^2 over the growing season (a whole year).

This means that PWU in the field is 300 litres/m^2 divided by 5 kg/m^2 = 300/5 = 60 litres/kg. In a greenhouse, PWU varies from 1,000/50 = 20 litres/kg to 1000/80 =12.5 litres/kg. This is on average a PWU of about 15 litres/kg in a greenhouse versus 60 litres/kg in the field; a four-fold improvement in Produce Water Use by moving from drip-irrigated field production to greenhouse production. Obviously, the exact values of PWU depend on the situation.

Closed greenhouses

Product Water Use can be reduced even further with the so-called 'semi-closed' and 'closed' greenhouses as we see in the Netherlands. These greenhouses are cooled with cold water that is pumped from deep ground water. A closed greenhouse has no vents, and a semi-closed greenhouse does have vents but uses them only in very hot weather. Semi-closed greenhouses are operated successfully on a large commercial scale, while completely closed greenhouses are, so far, mostly small-scale. As the vents are not opened (or at least not as much), it is possible to maintain a higher than usual level of CO_2, which increases production. Moreover, again thanks to the vents being closed or nearly closed, the water that evaporates from plants does not escape. Excess water vapour condenses against the cooling devices or other cool surfaces. In an experiment in the Netherlands with a closed greenhouse, it was estimated that about 40-50% of the water supplied to the crop had been recovered by condensation. The experiment recorded a PWU for



tomatoes as low as 4 litres/kg. In a closed greenhouse project in Spain, 75% of the irrigation water was recovered. The crop here was ocra, which can tolerate high temperatures.

PWU is adversely affected by the use of lots of water for evaporative cooling. Greenhouses in hot arid regions are often cooled with pad-and-fan systems and fogging, which requires massive amounts of water. Anecdotal data about such greenhouse operations in Mexico suggest that the PWU shoots up to over 60 or even more than 90 litres/kg.

Open hydroponic systems ('free drainage')

Growing in a greenhouse often means growing out of the soil, and in a growing medium such as rockwool, coco coir, peat, vermiculite, synthetic foams, and sometimes in pure hydroponics (water culture) or aeroponics. These systems can be 'open' or 'closed' (except water cultures, which are closed in principle). An 'open' hydroponic system, aka 'free drainage' system, drains the excess nutrient solution out continuously. This wastes a substantial amount of water and fertilisers and causes an undesirable burden on the environment. Normally the grower can choose the amount of drain, which is part 'management' as meant in Table 3. Drain is usually between 5% and 50% of the supply. The way to improve the water efficiency of these systems is by re-using the drain, or in other words, changing from an open to a semi-closed or closed hydroponics system.

Semi-closed hydroponic systems

In closed and semi-closed hydroponic systems, the nutrient solution is re-used. The excess nutrient solution that flows out at the end of the gullies is collected in a holding tank, or flows directly into the mixing tank. This tank is topped up continuously with fresh water to replace the water that is taken up by plants. The drain water may need to be disinfected to avoid spread of diseases. Topping-up can be done manually, by adding concentrated A and B nutrient solutions, plus acid or alkaline as required for pH control. Large commercial operations all use an advanced fertigation system that automatically injects (liquid) fertilisers into the top-up water.

It is very important to supply the right mix of nutrients, and that the amount of each individual element matches the needs of the plants. If the recipe is not tailored, plants don't get enough of some elements and too much of others. Plants selectively take up the desired nutrients and in that way they alter the nutrient solution. Preferred nutrients get depleted, while unwanted nutrients pile up. Often, sodium piles up too, especially where the fresh water contains more sodium than what is absorbed by the plants.

To avoid an imbalance in the nutrient solution, growers either 'bleed' or 'dump' the nutrient solution. 'Bleeding' means that, say, 10% of the drain is discharged continuously. 'Dumping' means that now and then the mixing tank is emptied and then refilled with a fresh load of water and nutrients. This makes the growing system semi-closed instead of closed. Bleeding and dumping reduce the Water Use Efficiency. It can be improved considerably by restricting the discharge. It helps to use laboratory tests to see whether (or when) bleeding or dumping is needed, rather than

dump every week by habit. Restricting the discharge saves on the costs of water and nutrients. It is also a shift to a closed hydroponic system.

Closed hydroponic systems

Advanced growers work with a closed growing system and do not bleed and never dump the nutrient solution. The nutrient solution is re-used or 'recirculated' and is topped up automatically and continuously with fresh water and with A and B concentrate, as described earlier. Topping up is done very precisely with the right amounts of each nutrient, namely, exactly the amount that the plants have consumed. Therefore, the grower sends a sample to a specialised laboratory. (Note: the lab can tell exactly how and where to take the sample and how to send it.) The lab report tells how much each element is out of balance. It also tells how the A and B solution have to be adjusted in order to correct (reduce or increase) the amount of each individual element. Such a nutrient test is done about weekly at the start. Later, when the system has settled down, it can be less frequent, say monthly or bi-monthly.

Based on the test report and recommendations, the grower adjusts the make-up of the A and B nutrient concentrates, or he/she programmes the fertigation computer with the new recipe. The nutrient solution in the mixing tank will soon contain what the plants need, and will remain stable. After an adjustment, no bleeding or dumping will be necessary for quite some time. Only when the conditions change (change in weather, start of flowering or fruit set, etc.), a new nutrient test needs to be done, and the recipe may need adjusting again. A closed hydroponic system uses 10-50% less water than an open system. Assuming that production remains the same, the Product Water Use is then also 10-50% better than in an open hydroponic system.

Sodium (salt)

Earlier we outlined that the nutrient solution can become unbalanced (i.e., some nutrients deplete and others accumulate). The shift in nutrient balance is not detected by an EC measurement as long as the total nutrient content remains the same. An imbalance often happens due to build up of sodium chloride (salt) that comes with the fresh water. Too high sodium levels are detrimental for plants. When the fresh water source has a high salt content, then more salt is added every time the nutrient solution is topped up. There is no easy solution for this problem. In some crops it is possible to shift to a plant variety that is less sensitive to saline conditions. But if the sodium keeps building up, at some point the limit will be reached. Then there is no other option than to refresh the nutrient solution by bleeding or dumping. A good approach is to measure the sodium concentration and only dump when it really becomes too high. Ideally, the problem should be solved at the source (i.e., at the fresh water intake). In locations with sufficient rainfall, it pays to harvest rain water from the greenhouse roof and store it in a tank, basin or dam. This becomes the clean, low-sodium fresh water supply that enables growing in a closed hydroponic system. This gives a very high water use efficiency.

Why tomato has a high Water Use Efficiency

In comparison to other products, greenhouse tomatoes are produced in a very water-efficient way. This is largely thanks to their extremely high yield. Many factors contribute to the high yield. Tomatoes contain a lot of water, which easily boosts the yield. Tomato also has a very high Harvest Index (this is the percentage of the plant biomass that is consumed). In greenhouse tomatoes, about 80% of the biomass produced consists of fruit, and only 20% forms the leaves, stems and roots. Lettuce too has a very high Harvest Index, as we eat the whole plant (apart from the roots). Many other crops have a much lower Harvest Index: wheat has a Harvest Index of about 50% at present, up from 30% some decades ago. Breeding has contributed a lot to the Harvest Index and plant productivity of tomatoes, wheat and many other crops. The performance of tomatoes is increased further by plant management such as systematic removal of laterals. Other factors include the long growing season, optimal growing conditions, CO_2 enrichment, excellent nutrition in hydroponics, good pest and disease control, plant balance steering, and the application of profound knowledge about tomato growing.

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